

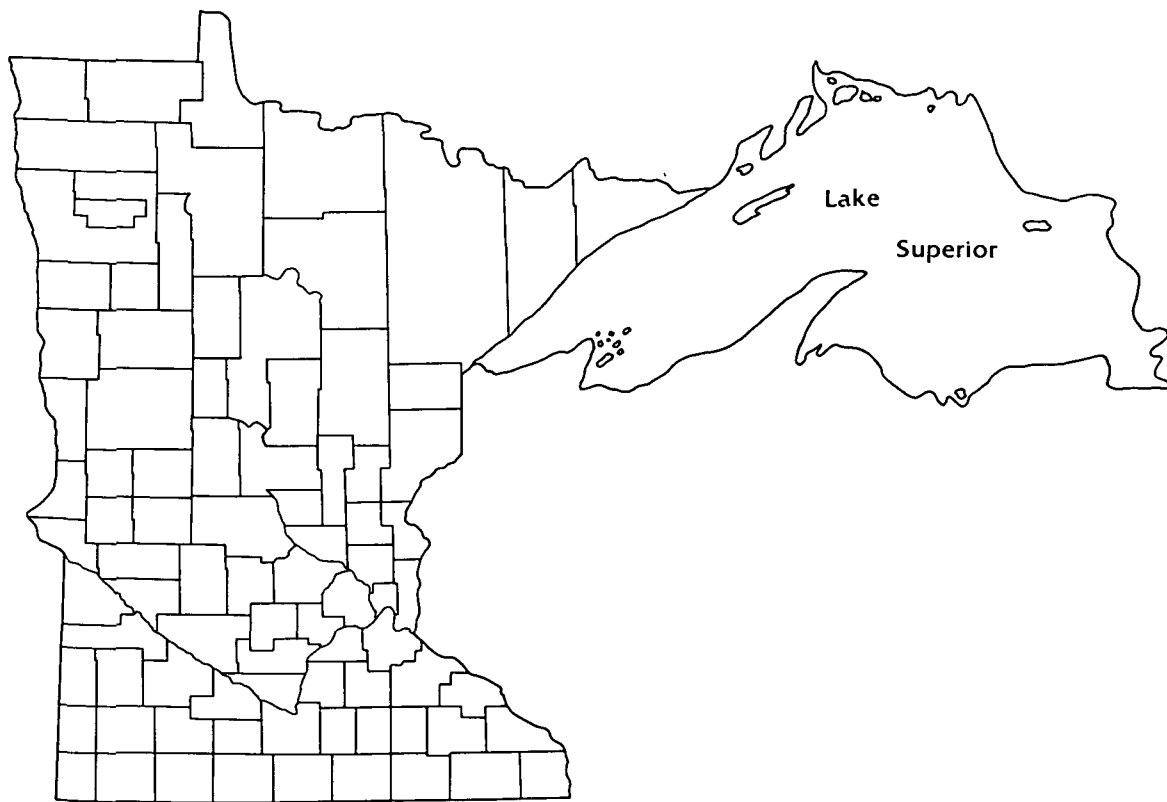
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**A STUDY OF
MINNESOTA LAND AND WATER
RESOURCES USING REMOTE SENSING**

December 31, 1982

NASA GRANT 24-005-263 VOL XV



MINNESOTA

SPACE SCIENCE CENTER

University of Minnesota

Minneapolis, Minnesota 55455

A STUDY OF MINNESOTA LAND AND WATER
RESOURCES USING REMOTE SENSING

FINAL REPORT

31 December 1982

Supported By:

NASA GRANT NGL 24-005-263

Submitted To:

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546

INTRODUCTION

Russell K. Hobbie

This final report for NASA Grant NGL 24-005-263 summarizes work done since the previous report in December, 1980. Four projects were completed during this time and are described here.

Dr. Thomas Lillesand and his colleagues at the Remote Sensing Laboratory report in Section A on the use of LANDSAT images to evaluate the trophic condition of lakes. The Minnesota Pollution Control Agency has been required by federal statute to evaluate every public lake in the state. This means that 3,000 to 4,000 lakes must be evaluated.

The Remote Sensing Laboratory did a pilot study of 60 lakes and found that the LANDSAT data correlate very well with the Carlson Trophic State Index. The CTSI is derived from measurements in the field. If good quality LANDSAT data are available in the future, this will be a good method to evaluate the lakes. Only state budget problems have precluded the start of an operational program - as distinct from a pilot study.

Section B describes work done at the University of Minnesota, Duluth by Dr. Michael Sydor and his colleagues. Benefits to the University and the state during the course of the contract are described. The Nimbus satellite data analyzed during the last two years clearly show the improvement in water quality of Lake Superior which has occurred since the dumping of taconite tailings stopped in March, 1980.

Soil science work is described in Section C. Most of the work was reported in our previous report (December, 1980), but some final analyses

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Matthew Walton, Minnesota Geological Survey

of the moisture stress evaluation are presented here by Drs. R. Rust and Pierre Robert.

Section D summarizes the work done by Dr. Matthew Walton and his colleagues at the Minnesota Geological Survey. The technical details were described in our 1980 report. The overall benefits of combining LANDSAT data with other kinds of information are reviewed here.

SECTION A

ASSESSMENT OF THE TROPHIC CONDITION OF SELECTED MINNESOTA LAKES THROUGH ANALYSIS OF LANDSAT DIGITAL MULTISPECTRAL SCANNER DATA

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ASSESSMENT OF THE TROPHIC CONDITION OF SELECTED
MINNESOTA LAKES THROUGH ANALYSIS OF LANDSAT DIGITAL
MULTISPECTRAL SCANNER DATA¹

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INTRODUCTION

This report summarizes a one year pilot project aimed at assessing if, and how, LANDSAT satellite data might assist the Minnesota Pollution Control Agency (MPCA) in complying with Section 314(a) of the Clean Water Act of 1977 (PL95-217). Section 314(a) mandates that each state identify and classify its public freshwater lakes according to their trophic condition. In Minnesota, this involves classifying some 3,000 to 4,000 lakes (depending upon the definition of "public lake"). The data collection and analysis necessary for such a classification entails numerous logistical problems and substantial costs. Faced with these problems, the MPCA contracted with the University of Minnesota Remote Sensing Laboratory (RSL) to perform the pilot project reported herein. The basic approach taken in the study was to compare MPCA-supplied ground data collected during 1980 on some 60 lakes to the digital multispectral image values measured by LANDSAT on the same lakes. Statistical models relating the two data sets were developed and they were subsequently used to estimate the trophic state of approximately

¹Research sponsored by Contract No. 32100-07621/32100-07622 from the Minnesota Pollution Control Agency (MPCA) and supported by NASA Grant No. NGL 24-005-263 and by the University of Minnesota's Agricultural Experiment Station (Projects 40-16 and 42-38).

100 additional lakes on the basis of the LANDSAT data alone.

This report summarizes the pilot project in the following manner. First, the geographical areas of investigation and the form of the LANDSAT and ground data made available for the study will be discussed. Second, the methods used to develop and calibrate the trophic status estimation models will be presented, along with a discussion of the overall statistical integrity of each model. Third, the methods used to classify the 104 "test" lakes with the LANDSAT data will be discussed. (A table listing the trophic state estimates for each of these lakes is presented in Appendix B and Appendix C of this report). Lastly, the conclusions and recommendations resulting from this effort will be summarized.

It is not our intention in this report to summarize the details of how the LANDSAT satellite multispectral scanner (MSS) works, nor how MSS data have been used to estimate water quality in a multitude of previous studies. These subjects are adequately treated elsewhere.¹² Here we summarize the work performed by the RSL in the pilot project and comment on the apparent effectiveness of this approach. We intend to present the technical details of our effort in the scientific literature at a later time.

STUDY AREAS/AVAILABLE DATA

Figure 1 depicts the location of the lakes used to calibrate our trophic state estimation models. These lakes appear in two LANDSAT scene areas (path/row 29/29 and 31/28), one covering the Twin Cities metropolitan area and its surroundings, and the other covering the Ottertail Lakes region

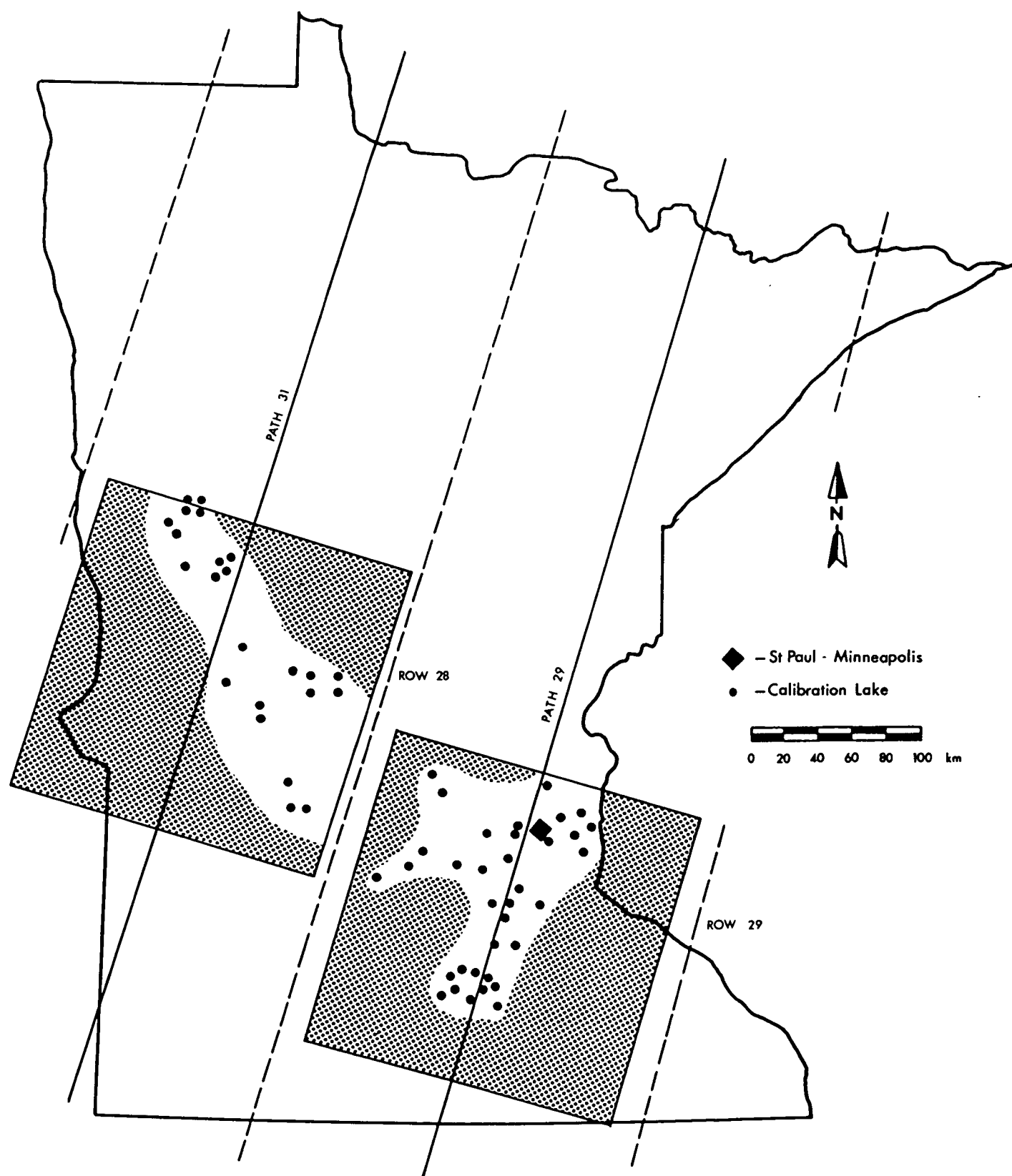


Figure 1. Study Areas

of West-Central Minnesota. These scene areas were chosen by MPCA as being typical of the range of lake conditions found throughout most of the state. In addition, the location of the study areas comparatively close to the Twin Cities enabled thorough field analysis within the limits of project funds.

LANDSAT Data

It was our original intention to analyze data from several dates for each scene area. Regrettably, adverse weather conditions and NASA data processing difficulties limited the availability of LANDSAT imagery to two dates in the Ottertail Lakes region (June 25 and August 18, 1980) and one date in the metropolitan region (July 29, 1980). One of these scenes, the June 25 Ottertail Lakes image, was omitted from full analysis because of insufficient concurrent ground data (only six lakes had been sampled). Thus the analysis was performed on one date within each area, and no atmospheric normalization between scenes was necessary.

Figures 2, 3, and 4 are full-scene photographic prints of the LANDSAT scenes which were analyzed. Figures 2 and 3 show the two consecutive frames of imagery covering the Ottertail Lakes region for August 18, 1980. All of these images are from the Band 7 (near infrared, 800 - 1100 nm) channel of the LANDSAT Multispectral Scanner. This channel, one of four in the MSS, provides the maximum contrast between the lakes and surrounding land.

The Ottertail Lakes area appears in the top center through the lower right portion of Figure 2. Due to orbit-to-orbit variation in the scene center location, this image did not include the entire study area (as had been intended), requiring the additional use of the next scene to the north (Figure 3). The quality of these images was very good, except where clouds

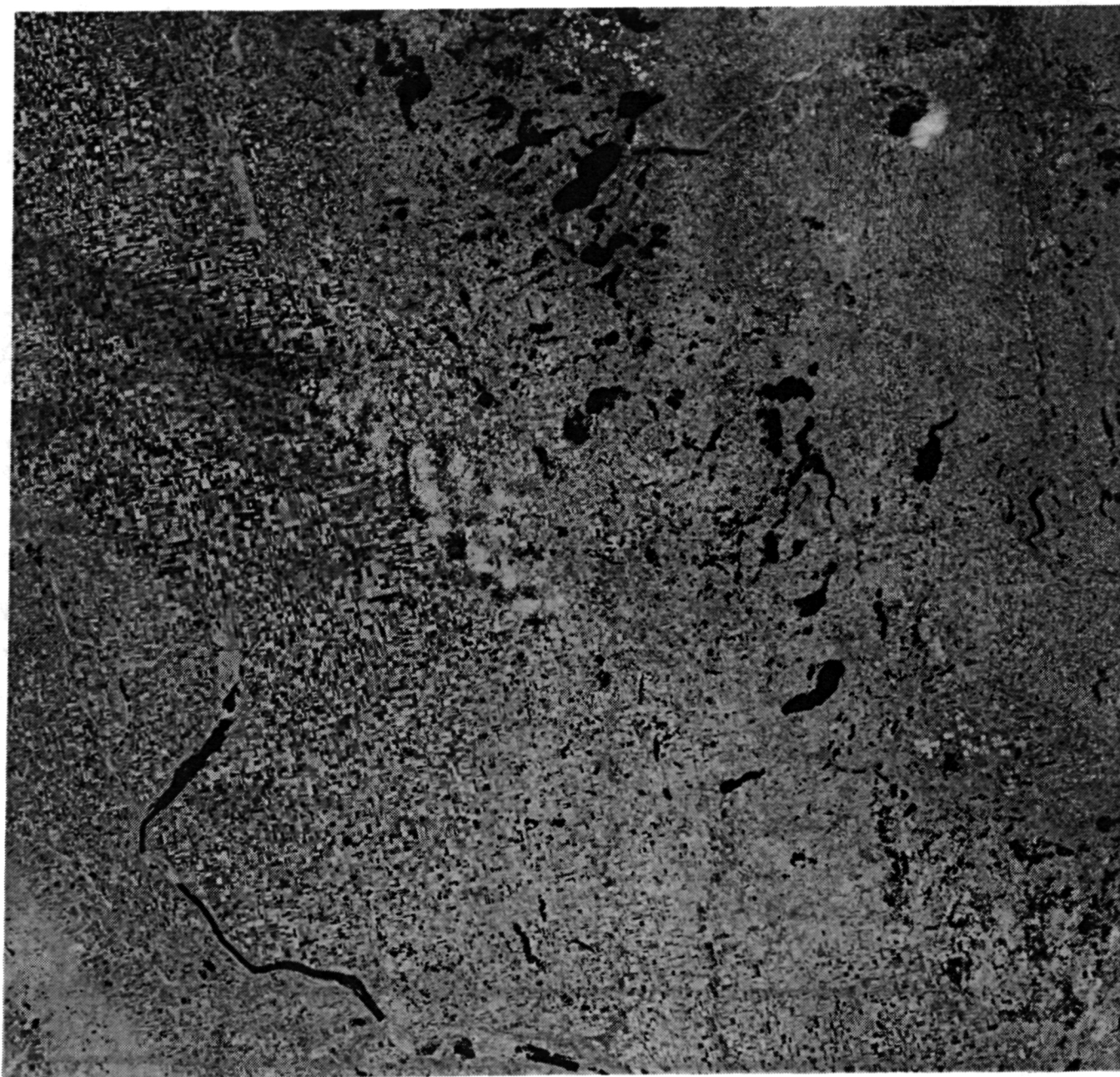


Figure 2. August 18, 1980, LANDSAT MSS Band 7 image of Ottertail Lakes study area (Path 31, Row 28).

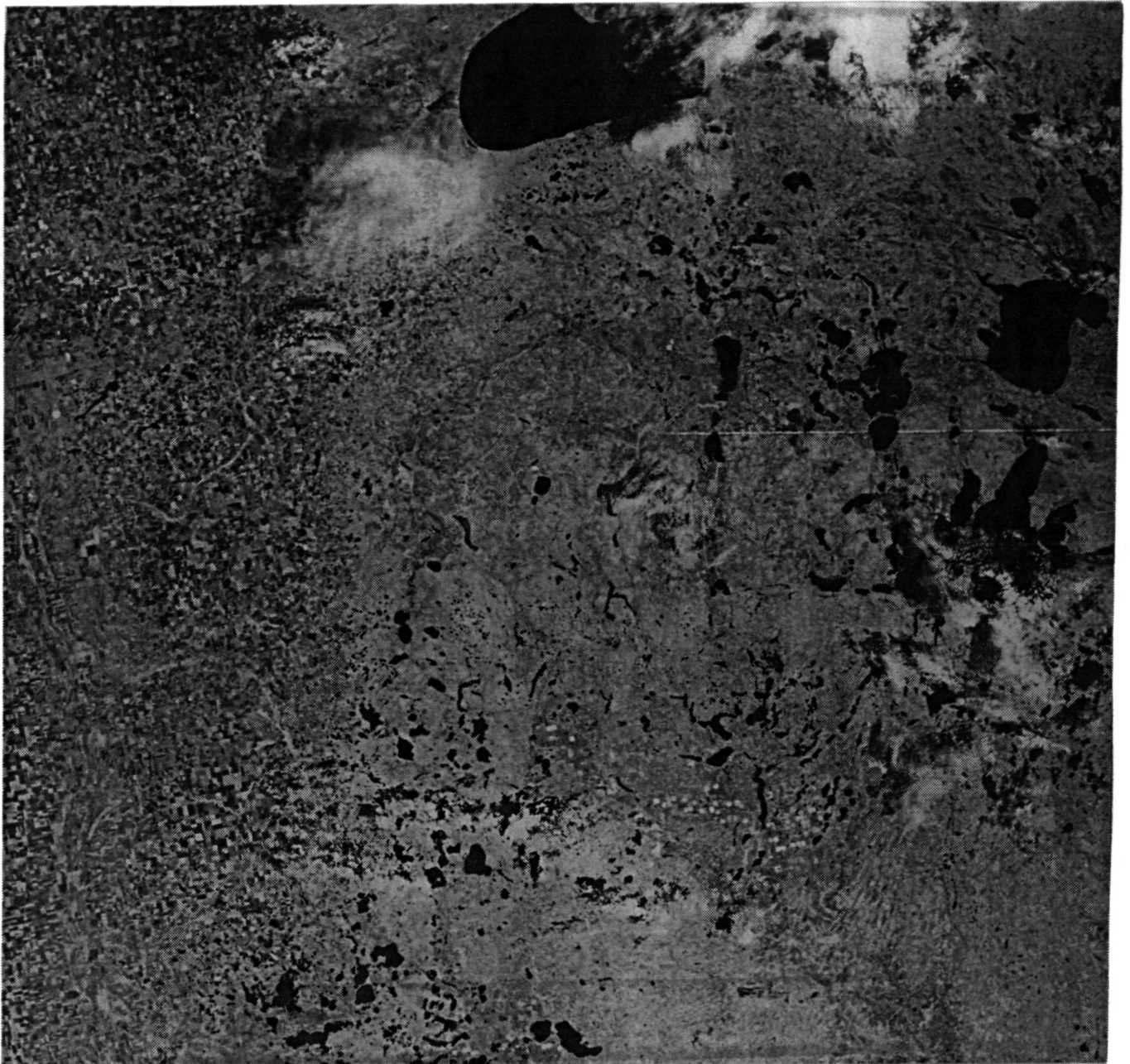


Figure 3. August 18, 1980, LANDSAT MSS Band 7 image providing supplemental coverage of Ottertail Lakes study area (Path 31, Row 27).



Figure 4. July 29, 1980, LANDSAT MSS Band 7 image of Twin Cities metropolitan study area (Path 29, Row 29).

obscured a number of the study lakes.

Figure 4 shows the Twin Cities Metropolitan area in the top center portion of scene 29/29. This scene was of marginal quality, included some cloud cover (center of left edge) and numerous bad data lines. Whereas the Ottertail Lakes images had been fully processed by NASA (including geometric correction and full-scene photographic generation), the Metropolitan area scene had been lost in the NASA processing stream. Fortunately, a pre-correction computer compatible tape of this scene was obtained, from which the full-scene print shown in Figure 4 was generated by the RSL on a Dicomed image recorder. Although this image is not geometrically corrected, it was fully usable for this study.

Ground Data

The ground data supplied for each of the two study areas were of two forms. The first was MPCA-collected observations of secchi disk depth (in meters) chlorophyll-a concentration ($\mu\text{g/l}$), total phosphorous ($\mu\text{g/l}$), turbidity (FTU), color (Pt-Co), and total nitrogen ($\mu\text{g/l}$). These samples were taken via float plane within 1-1/2 days of the LANDSAT overpass.

The second source of ground data was the Citizen Lake Monitoring Program (CLMP), coordinated by MPCA. The CLMP set contained data only for secchi disk depth and limited observations for total phosphorous and color. Because variations in sampling error between observers was anticipated, the CLMP data were not used in the modeling process, but were used as supplementary data to evaluate the model results. The model was developed using the MPCA-collected data only.

In the case of the Ottertail Lakes scene, ground data from a total of

32 sample points located on 25 "calibration" lakes were made available for modeling. Wind problems precluded the collection of secchi disk data at eight of these sampling points, and clouds obscured the LANDSAT image of seven of the lakes. For the Metropolitan scene, data on 31 sample points located on 28 calibration lakes were used in the modeling process.

Supplemental Aerial Photographs/Bathymetric Charts

To assist in analyzing the LANDSAT data, the RSL acquired aerial photographs of all calibration lakes at the time of LANDSAT overflight. These images were recorded on color and color infrared film, at a scale of 1:65,000, using a motor-driven 35 mm Nikon F2 camera. Enlargements of the infrared photographs were assembled into mosaics depicting each calibration lake at a scale of 1:18,000. The resulting mosaics were valuable for documenting lake conditions in much finer detail than was available from the LANDSAT data and for aiding the image analysts in interpreting the digital portrayal of the lakes. Such features as aquatic vegetation, bottom effects, algae blooms, sediment plumes, etc. could be clearly seen on the aerial imagery.

The aerial photographs were referenced in conjunction with MPCA-supplied bathymetric charts for each lake. In addition to the depth contours, the locations of all sampling points were indicated on these charts.

MODEL CALIBRATION

Parameters Modeled

Per mutual agreement between the MPCA and the RSL, two directions were pursued in the modeling effort. The first was to develop statistical models through which the LANDSAT data could be used to estimate the Carlson Trophic State Index (TSI).³ The second was to investigate the development of models for estimating each of the six "raw" water quality measurements made on each lake. Accordingly, MPCA supplied four Carlson TSI values in addition to the six raw measurements for each calibration lake. The first three TSI values were computed from the secchi, chlorophyll-a, and total phosphorus readings. The fourth was the average of the first three. Suspecting great variability in the phosphorus-derived TSI value, MPCA expressed an interest in modeling a fifth TSI value, which was the average of the TSI's computed from the secchi disk and chlorophyll-a parameters only. Thus, 11 parameters (five TSI's and six raw values) were modeled during the study. Statistical variates of the ground data (such as principal components) were not modeled, since MPCA wished to relate any final lake classification parameter directly to corresponding raw field data.

LANDSAT Data Extraction Procedures

The LANDSAT data samples were extracted from the full scene digital data tapes obtained from NASA. To facilitate this process, segments of the full scene were displayed on an interactive image analysis system at the RSL. This equipment allows the analyst to view the LANDSAT data in contrast-enhanced color, automatically mask out land features in the scene,

electronically magnify the image to observe the full detail in the data, and outline ground areas over which digital data should be extracted. Some 37 image segments in the Ottertail Lakes scene and 46 in the Metropolitan scene were analyzed. Each segment contained 240 rows and 240 columns of picture elements (pixels). Pixels in the Ottertail Lakes area were nominally 60m square at ground level. Those in the Metropolitan scene were 60m x 80m in size.

Five different sampling methods were used to collect the LANDSAT data on each calibration lake, enabling a comparison between techniques. Each of these methods is outlined below:

- single point: the single LANDSAT pixel corresponding to the water sample location was sampled. The sample position was located on the display by viewing the bathymetric chart for the lake under analysis. This type of sample avoids the potential problem of variation in the lake water condition away from the sample point.
- 3x3 and 5x5 neighborhoods: the computer also automatically sampled squares of 3x3 and 5x5 pixels surrounding the single point. Because the LANDSAT data contain a slight amount of electronic noise, these methods were intended to "smooth out" the spurious variations which may have occurred at the single pixel. Thus, the averaged value may be a more accurate indication of the ground radiance at the water sample point. When sampling very small or narrow lakes, the neighborhoods occasionally included some land pixels. These values were detected by their high variances and omitted from any subsequent analysis.
- interior sample: observing the bathymetric chart and aerial photographs,

the analyst outlined a "deep water" region of depth greater than twice the secchi disk measurement for each calibration lake. This avoided "bottom effect," where the scanner views the lake bottom as well as the water. The analyst also avoided weedbeds, marinas, clouds, cloud shadows, and other anomalies observed either on the enhanced LANDSAT display or on the low altitude photography. This sampling approach further extends the "data smoothing" concept of the neighborhood samples, at the expense of possibly integrating over a variety of water quality zones within a lake.

- exterior sample: this approach involved outlining the entire lake, taking care not to include any other lakes within the outline. After collecting all of the LANDSAT data within the outline, a Band 7 threshold was used to discard all nonlake pixels. This approach provides no analyst intervention to avoid problems such as bottom effects. However, it is considerably more convenient operationally.

Each of the above techniques was employed on all of the calibration lakes by two image analysts working independently. This provided a means of cross-comparing variations between operators and methods, as well as providing checks on all data used in model development. The various sampling techniques were compared by computing correlation coefficients between the LANDSAT MSS and the TSI variables. The correlation coefficients for the Ottertail Lakes data consistently showed that the interior samples best fit all TSI's. This indicates that the smoothing effect of the larger sample was more important than the localized attribute of the point and neighborhood samples. Further supporting this finding were the exterior

data, which also provided significantly higher correlation coefficients than the point or neighborhood data. The Metropolitan scene data exhibited a much smaller range in correlation values but the sampling techniques were ranked in the same order as with the Ottertail data. Also, significant differences between operators were observed for the point, 3x3 pixel and 5x5 pixel methods. Differences between operators were insignificant for the interior and exterior sampling methods. Based on these results, the modeling effort focused on the interior and exterior LANDSAT samples only.

Modeling Results

The data extraction process provided a series of tables listing, for each of the calibration lakes, the mean radiance and variance in each of the four LANDSAT MSS channels and the corresponding eleven MPCA water quality measurements. A separate table was generated for each of the two scene areas and two LANDSAT sampling techniques (interior and exterior).

All model development was performed using the Multreg Statistical Analysis Package developed at the University of Minnesota.⁴ A series of regression models was derived, each estimating one of the 11 water quality variables from the LANDSAT data. In addition to the original LANDSAT variables, several transformed values were used. These included radiance squared and various ratios of two channels. A variable screening algorithm in Multreg was used to select the most effective combination of variables for each model. Several models were developed for each water quality variable. The statistical criteria used to select the "best" model for each parameter were many and varied. Suffice it to say here, the models chosen were those thought to have the best overall predictive accuracy when applied

to the range of lakes to be classified in the two scenes. The interior models proved to be superior to the exterior models in this regard. Hence, we will provide additional details only for this final set of models.

TSI Models

Table 1 lists the LANDSAT variables used in each of the final models for estimating the Carlson TSI values. The numbers 4-7 refer to the LANDSAT MSS channels (channels 1-3 were for a different sensor system no longer operational). Band 4 represents green reflectance (500-600 nm), band 5 is red reflectance (600-700 nm) and 6 and 7 are near infrared reflectance (700-800 and 800-1100 nm, respectively). The squared terms refer to the channel variables squared, and the 4/5 refers to the ratio computed between band 4 and 5 brightness values. Table 1 also lists the regression correlation coefficients (r^2), the standard errors of estimate (rms residuals), and a measure of percent inaccuracy for each model. The regression correlation coefficient is a measure of the fit of the regression equation to the data with a maximum possible value of 1.0. The more variables included in a model, the higher r^2 will be, so direct comparisons between models using this statistic can be made only when the models under analysis have equal numbers of variables. The standard error of estimate has the same units as the predicted quantity, and is the standard deviation. Approximately 68 percent of the measurements are expected to be within one standard deviation of the mean. The estimated percent inaccuracy is simply the ratio (expressed as a percentage) of the standard error to the mean of the observed values used to develop the model.

Table 1. Summary of prediction models for Carlson TSI values.

Ottertail Lakes Area (August 18, 1980)			
Variables (MSS bands)	r^2	rms	rms/mean (%)
Secchi (a) 5, 6, 7, 5 ²	0.94	1.93	3.9
Chlor (b) 5, 6, 7, 5 ²	0.84	3.88	7.0
TP (c) 6, 7, 4/5	0.43	8.25	15
Ave (a, b, c) 6, 7 ² , 4/5	0.87	3.51	6.4
Ave (a, b) 6, 7, 4/5	0.92	2.72	5.1
Metropolitan Twin Cities Area (July 29, 1980)			
Variables (MSS bands)	r^2	rms	rms/mean (%)
Secchi (a) 4, 5, 6 ² , 7 ² , 4/5	0.88	4.13	7.5
Chlor (b) 4, 5, 6, 7, 4/5	0.84	6.38	10
TP (c) 6, 4 ² , 5 ² , 7 ² , 4/5	0.69	8.79	14
Ave (a, b, c) 4, 5, 6, 7 ² , 4/5	0.87	4.82	8.0
Ave (a, b) 4, 5, 6, 7, 4/5	0.90	4.35	7.5

The results shown in Table 1 indicate that the total phosphorous variable could not be accurately fitted. This had been anticipated by MPCA personnel, because of the inherent variability in this parameter. In addition, Table 1 shows that a higher overall level of success was realized with the Ottetail Lakes area data. This was also anticipated by the MPCA personnel, due primarily to a much larger range of lake conditions across the Metropolitan scene. The number of variables required to obtain a suitable model was higher for the Metropolitan scene data, indicating the need for more complex models. As expressed by the rms residuals (a measure of the average error found when applying the model to the calibration lakes), the TSI estimates for the Ottetail Lakes area data were generally accurate to ± 4 TSI units, whereas the Metropolitan scene accuracy ranged ± 6 units (excluding the total phosphorous TSI variable). Appendix A lists the coefficients for each of the TSI models summarized in Table 1.

Models for "Raw" Data

Table 2 summarizes the results of modeling the raw data from the LANDSAT values. Among other things, this table illustrates the generally poor performance of the "raw" models in comparison to their TSI counterparts (in terms of the higher rms/mean values). In short, the transformation into TSI values generally improves the statistical integrity of the models. At the same time, the TSI transformation makes for less complex model forms. In general, the raw values were not modeled well enough to use them as a basis for subsequent classification of the test lakes. Accordingly, classification was undertaken using the TSI parameters only.

Table 2. Summary of prediction models for "raw" water quality parameters.

Ottertail Lakes Area (August 18, 1980)

Variables (MSS bands)	r^2	rms	rms/mean (%)
Secchi 5, 6, 7, 5 ² , 6 ² , 7 ² , 4/5	0.98	0.16	6.4
Chlor 4, 5, 6, 4 ² , 5 ² , 6 ² , 7 ² , 4/5	0.95	5.90	31
TP 4, 5, 7, 4 ² , 5 ² , 4/5	0.73	20.2	47
Turbidity 4, 5, 7, 4 ² , 5 ² , 4/5	0.87	0.89	37
Color 4, 6, 7, 4 ² , 6 ²	0.75	4.76	33
Nitrogen 4, 5, 7, 4 ² , 5 ² , 7 ² , 4/5	0.79	186	19

Metropolitan Twin Cities Area (July 29, 1980)

Variables (MSS bands)	r^2	rms	rms/mean (%)
Secchi 4, 6, 5 ² , 6 ² , 7 ² , 4/5	0.91	0.57	30
Chlor 6 ² , 7 ²	0.77	38.2	67
TP 5, 6, 5 ² , 7 ²	0.69	76.4	67
Turbidity 6, 6 ² , 7	0.90	2.27	37
Color 4, 5, 6, 7, 5 ² , 6 ²	0.83	4.85	25
Nitrogen 4, 5 ² , 6 ² , 7 ² , 4/5	0.90	326	20

LAKE CLASSIFICATION

Data Extraction

The aforementioned models were used to predict the Carlson TSI values for 32 lakes in the Ottertail scene and 72 in the Metropolitan scene. The data extraction procedure used to collect the LANDSAT values for these lakes varied only slightly from that used to develop the interior models. In the modeling effort, the secchi disk reading for each lake was available and was used to define the sampling area to be used in the model. That is, the analyst avoided any areas of the lake having a depth less than twice the secchi reading. In the classification process, the secchi depth reading was not known. Accordingly, LANDSAT pixel values were generally extracted from all areas of a lake having depths greater than 15'. It was felt that this criterion would minimize data degradation from such influences as bottom effect and submerged vegetation. In collecting the data, the image analyst again avoided any extraneous scene elements such as algae blooms. Any unique tonal qualities or other characteristics of the lakes were noted on a lake-by lake basis.

When lakes contained several geographically distinct lobes or bays, and/or apparently distinct trophic zones, separate samples were taken in each sub-area. Where possible, lakes having multiple samples were divided geographically according to MPCA's bay identification system. In all cases, the sub-areas used were delineated on the bathymetric chart for the lakes.

Lakes with depth less than 15' were visually evaluated, and samples were taken only if bottom effects were not evident to the analyst. In such

cases, the sampling was performed within the confines of the 10' contour. In a limited number of cases, depths of less than 10' were sampled if bottom effects were not evident in the LANDSAT data. Again, notes were taken to document the particulars of the sampling process employed on each lake.

Classification Results

The predicted Carlson TSI values for the lakes in the Ottertail and Metropolitan scene comprise the tables in Appendix B and Appendix C, respectively. The tables are organized by county, using the MPCA lake identification numbering system and the MPCA-supplied estimate of surface area. This information is followed by the predicted secchi, chlorophyll-a, and total phosphorous TSI values for each lake. The "TSI AVE. a, b, c" column contains the predicted values for the average of the secchi, chlorophyll-a, and total phosphorous parameters. It should be noted that this column is not simply the arithmetic average of the previous three. Rather, it contains the results of a separate prediction model for the average. The "TSI AVE. a, b" column contains similar information for the predicted value of the average of the secchi and chlorophyll-a values. All values represent the average observation of two image analysts. The "Remarks" column states any qualification about the predictive values, such as depths used were less than 15', etc.

In cases where the predicted TSI was above the range used to develop the prediction model, no attempt was made to extrapolate beyond the upper model bound. These cases are indicated with "greater than" (>) symbols.

It can be seen from the classification tables that not all of the test lakes could be classified. This happened for various reasons. Some lakes

were cloud covered in the LANDSAT image or were located outside the scene area. Some lakes were located in areas of inferior image data or noise. Others were so shallow that bottom effects clearly precluded accurate model prediction. Others were so small that fewer than 20 pixels of reliable lake data could be collected. In such cases, there was great variation between the data obtained by the two image analysts--indicating inadequate sample size and extraneous pixel values.

Also deleted from the classification analysis were lakes that manifested dramatic tonal anomalies on the interactive display. Algae blooms, bottom effects, extensive weedbeds, among other things, could have been responsible for these anomalies. Reliable TSI predictions could not be made under these conditions.

Overall, approximately 85 percent of the lakes in the Ottertail scene and 60 percent of the lakes in the Metropolitan scene were classified. A number of lakes contained sub-areas in distinct trophic states. These areas are indicated by (01), (02), etc. Their location has been annotated on the appropriate bathymetric charts.

Reliability of Classification

Ideally, one could assess the reliability of the LANDSAT classification by comparing the LANDSAT and MPCA data for a large random sample of the classified lakes. Regrettably, logistics and monetary constraints did not permit concurrent MPCA data collection for this purpose. Hence, historical MPCA data will have to be used to assess the overall reliability of the LANDSAT classification. However, it is possible to make some a priori judgements of classification comparative reliability for the various models

by other means. Figures 5 and 6 are included for this purpose. They show graphs of the relative performance of the final prediction models for each scene. Plotted on these graphs are the model-predicted vs. ground-observed measurements for the calibration lakes. Where available, model-predicted vs. CLMP-supplied values have also been plotted on these graphs, with a separate symbol (x). These graphs permit a visual evaluation of the overall fit of the regression equations. If a given equation resulted in perfect correlation between the predicted and measured quantities, then all points would fall on the 1:1 line.

Considered in concert with the statistics in Tables 1 and 2, Figures 5 and 6 illustrate the comparatively high reliability of the LANDSAT-predicted TSI values (except the phosphorous predictions). The overall average discrepancy observed between the LANDSAT-predicted values and the available CLMP values was only 2.6 TSI units for the secchi measurements (3 Ottertail lakes and 12 Metropolitan lakes). The comparable value for total phosphorous was 10.4 TSI units (2 Ottertail lakes and 7 Metropolitan lakes).

CONCLUSIONS

Though of limited scope and duration, this one-year pilot project has indicated the following:

1. LANDSAT data appear to have great utility in assessing the trophic state of Minnesota lakes. In this study, LANDSAT MSS data were found to be particularly reliable predictors of secchi-derived Carlson TSI values, moderately reliable predictors of chlorophyll-derived values,

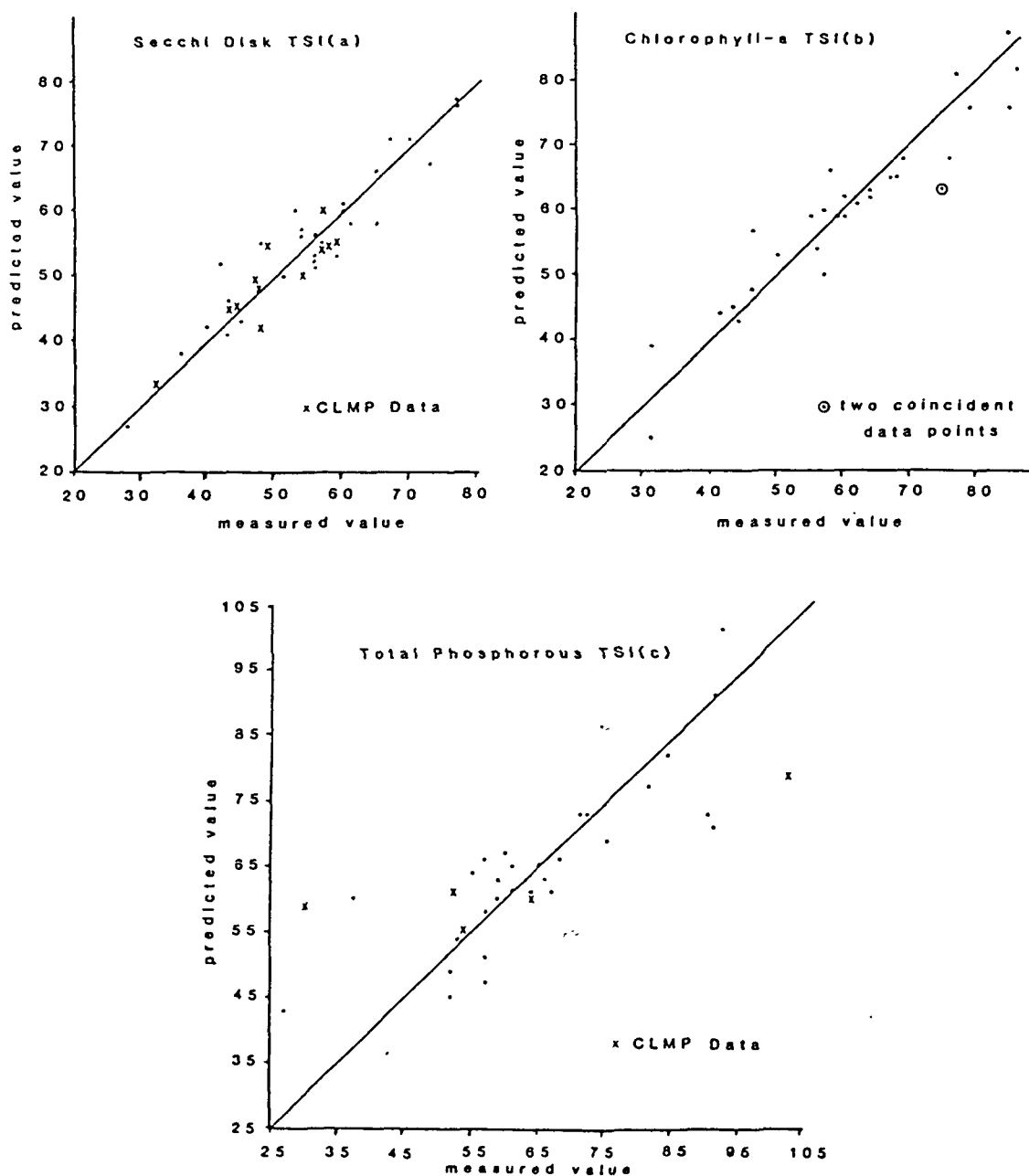


Figure 5(a). Measured vs. predicted values for Secchi, Chlorophyll-a, and Total Phosphorous TSI models for Ottertail Lakes LANDSAT scene.

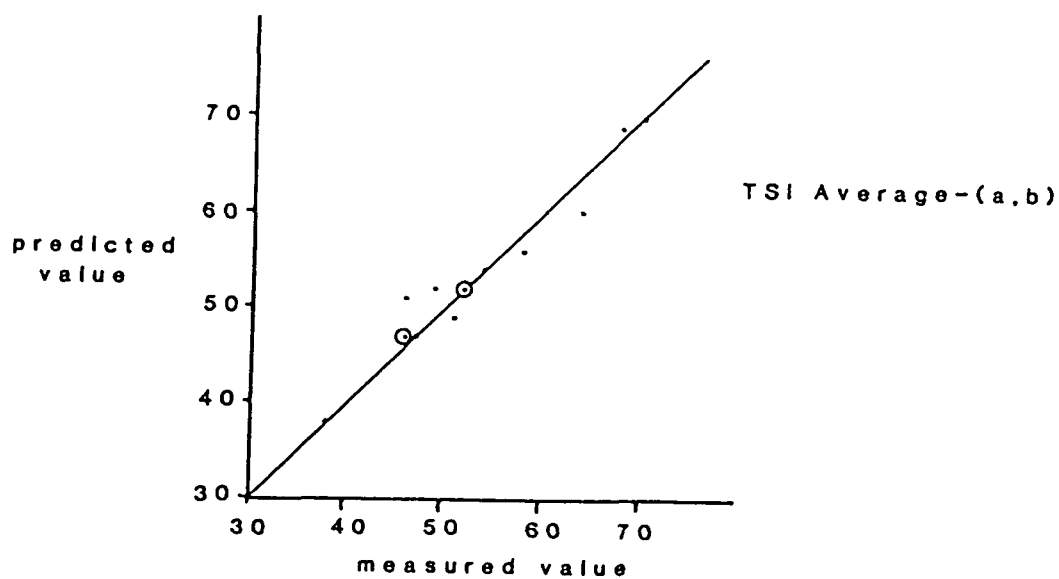
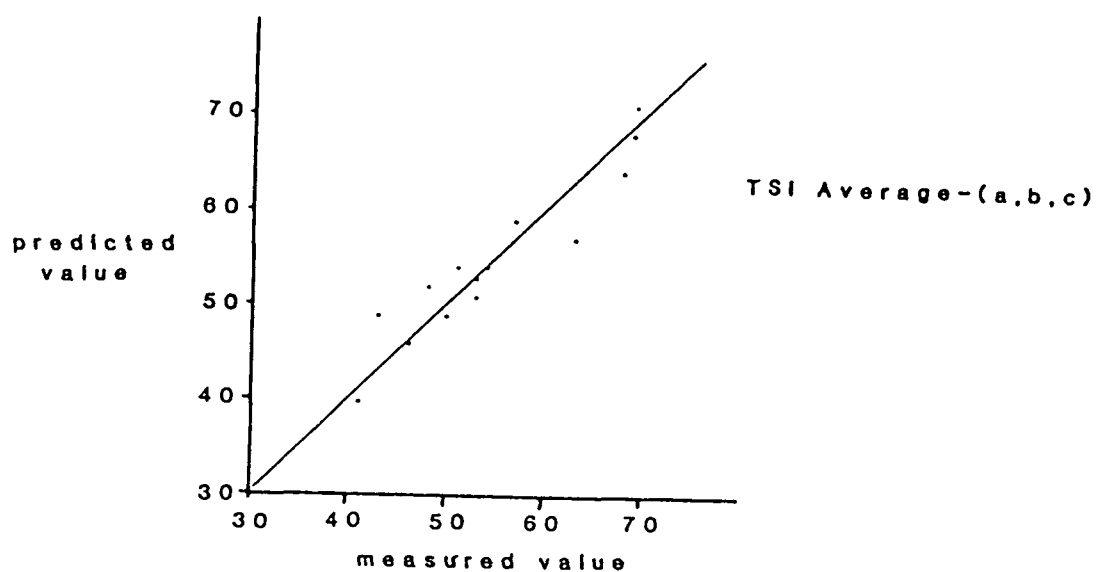


Figure 5(b). Measured vs. predicted value for average TSI models for Ottetail Lakes LANDSAT scene.

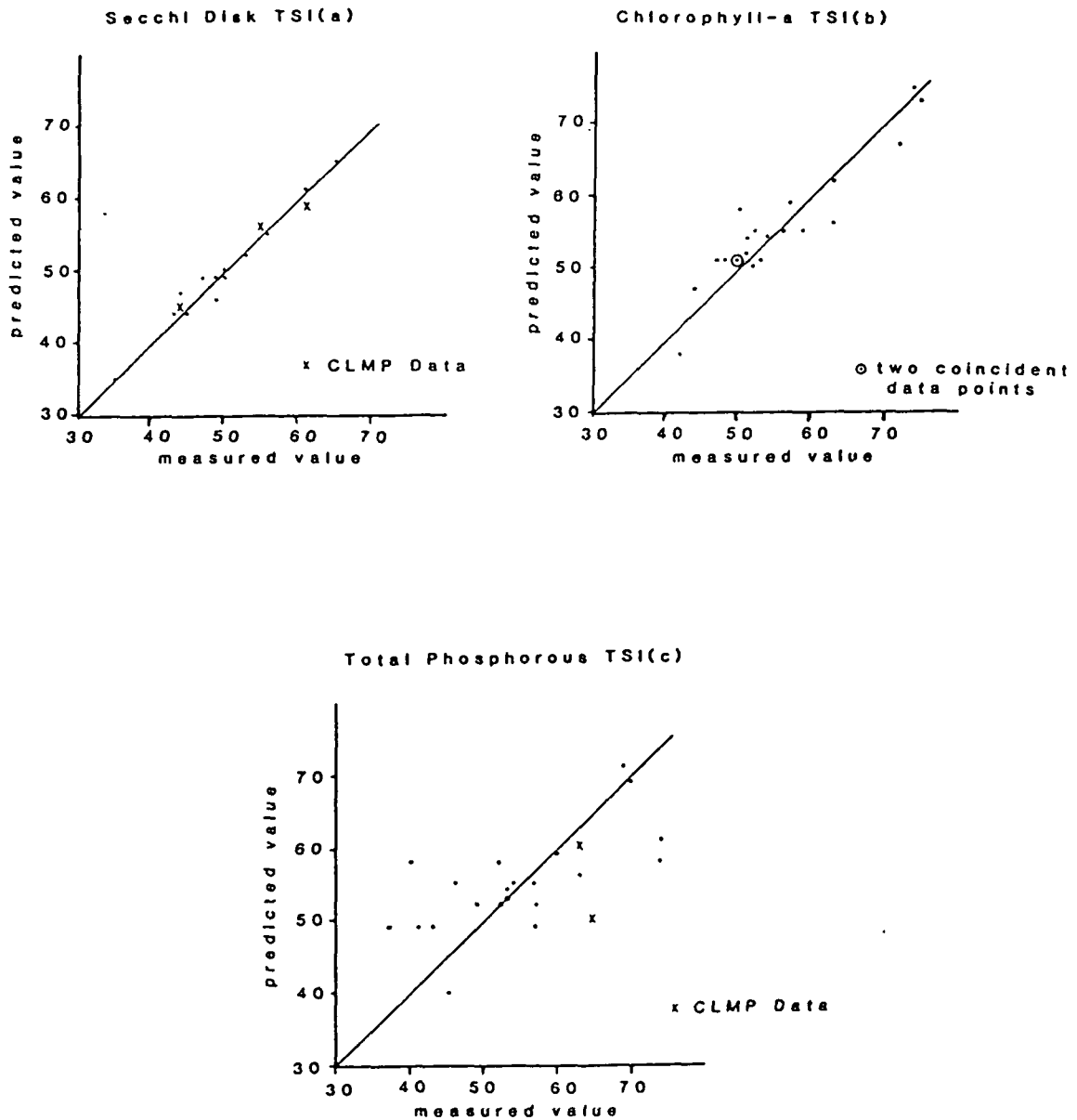


Figure 6(a). Measured vs. predicted values for Secchi, Chlorophyll-a, and Total Phosphorous TSI Models for Metropolitan Lakes LANDSAT scene.

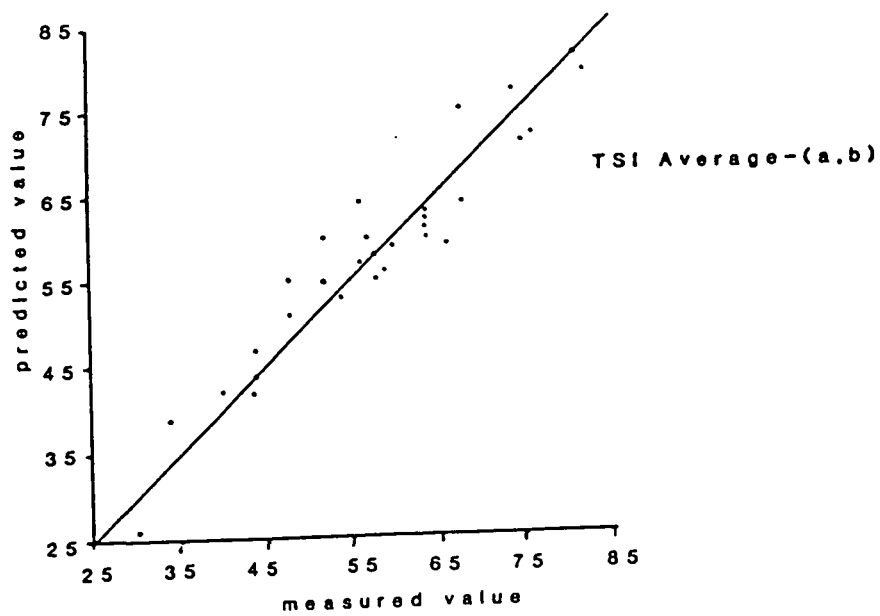
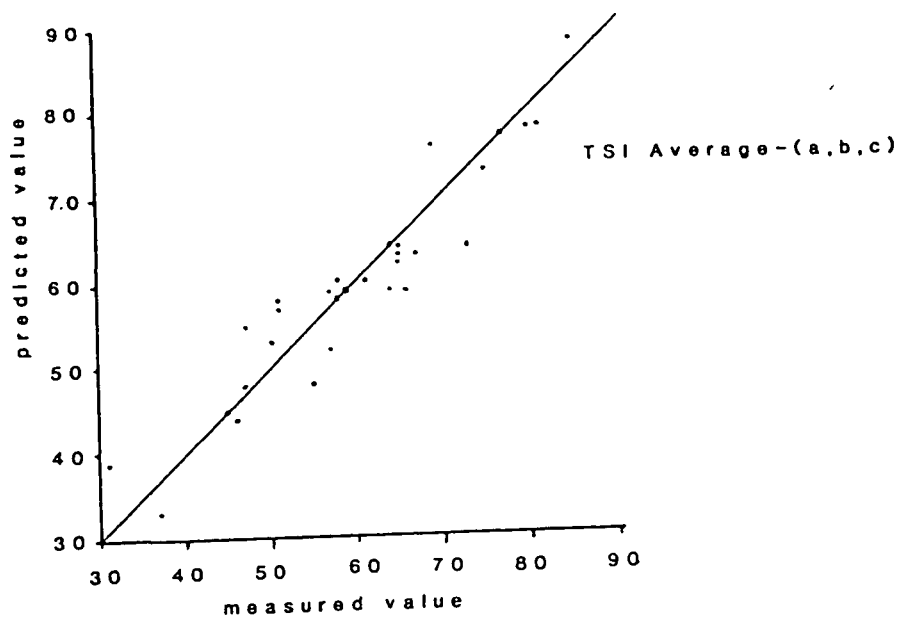


Figure 6(b). Measured vs. predicted value for average TSI models for Metropolitan Lakes LANDSAT scene.

and comparatively poor predictors of phosphorous-derived values. The LANDSAT models were also found to be reasonably reliable predictors of average TSI values.

2. The overall practical utility of the LANDSAT approach to trophic state prediction is a strong function of the quality of the LANDSAT data available, the range of lake conditions appearing in any given scene, and the manner in which the LANDSAT data are extracted. In this study, weather conditions, logistics, and NASA data processing problems precluded multitemporal analysis of the study lakes. Clouds and data of inferior quality caused problems in the single-date analyses performed in this study. Also, the entire methodology appears to be much more applicable to the Ottertail Lakes region than to the Metropolitan region. The principal problem in the Metropolitan scene was the comparatively small size of the lakes to be classified. For the conditions of this study, the interior lake sampling strategy appeared to improve significantly the quality of the LANDSAT predictions.

RECOMMENDATIONS

1. The procedures developed in this study should be tested in other geographical locations of the state.
2. Further application of the LANDSAT methodology should be done on a scene-by-scene calibration basis and separate models should be investigated for different lake types, time of year, etc.

3. The LANDSAT methodology should not be employed on extremely shallow lakes (circa 5'), nor small lakes (fewer than 30 acres of open water having a depth of more than 10').
4. Research should be initiated to define manners in which the LANDSAT classification methodology might be implemented on a more automated basis and on microprocessor-based hardware. The underlying object of these efforts should be the development of an operational monitoring procedure which MPCA could employ on a long-term in-house basis.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the cooperation of the Minnesota Pollution Control Agency in the performance of this study. All MPCA personnel involved with this project were important contributors to its success. Anne LaMois Down, Katherine A. Knutson, and Clara M. Schreiber are acknowledged for their help in the production of this manuscript. Finally, many aspects of this study were supported directly or indirectly by funding from NASA Grant No. NGL 24-005-263, and the University of Minnesota's Agricultural Experiment Station (Projects 40-16 and 42-38).

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Appendix A. Coefficients for Carlson TSI Prediction Models

Coefficients for Carlson TSI Prediction Models

Ottetail Lakes Area 18-AUG-80		4	5	6	7	4 ²	5 ²	6 ²	7 ²	4/5
Secchi (a)	55.40603		1.251824	7.733898	-13.90199		-40.21266			
Chl. a (b)	-108.6349		18.94025	8.904933	-15.03513		-0.6758321			-48.70506
TP (c)	75.31036			9.731075	-16.50316				-3.533835	-35.56183
TSI AVE. (a,b,c)	39.76273			10.12104						-39.65946
TSI AVE. (a,b)	57.25476			10.35393	-16.74187					
Metropolitan Area 29-JUL-80		4	5	6	7	4 ²	5 ²	6 ²	7 ²	4/5
Secchi (a)	270.9353	15.57264	-18.72279	4.616051	-13.50697			0.8700405E-1	-1.553990	-181.9944
Chl. a (b)	420.9255	24.16596	-32.11311	6.428936		0.4040416	-1.018016		-2.9977635	-289.5418
TP (c)	287.0626			3.907258					-1.913536	-174.8886
TSI AVE. (a,b,c)	390.1230	21.45709	-30.26651							-255.4268
TSI AVE. (a,b)	326.0379	18.67490	-23.88981	3.450994	-9.806076					-223.5438

Appendix B. Classification of Lakes in the Ottertail Lakes Study Area

Classification of Lakes in the Ottertail Lakes Study Area

COUNTY	LAKE I.D. NUMBER	LAKE NAME	Acres	SURFACE AREA Hectares	(a) SECCHI	(b) CHLOROPHYLL-a	(c) TOTAL PHOSPHOROUS	TSI AVE. a,b,c	TSI AVE. a,b	REMARKS
Becker	3-382	St. Clair	242	97.9	>65	>75	>74	>69	>70	<5', v. 1t. tone
"	3-475	Melissa	1,827	739.4	49	59	53	53	52	
Big Stone	6-152	Big Stone	6,028	2,439.5	>65	>75	>74	>69	>70	Usage of mult. sample
Douglas	21-51	Henry	152	61.5	>65	75	>74	>69	>70	
"	21-53	Agnes	162	65.6	>65	>75	>74	>69	>70	
"	21-54	Victoria	447	180.9	48	57	53	57	51	
"	21-56	LeHommeDieu	1,892	765.7	46	52	51	54	49	
"	21-57	Carlos	3,017	1,221.0	43	56	47	51	46	
"	21-81	Winona	220	89.0	-	-	-	-	-	<5', tonal anomaly
"	21-83	Miltona	5,924	2,397.4	46	54	50	53	48	
"	21-123	Ida	4,506	1,823.6	45	54	50	53	47	
"	21-216	Whiskey	165	66.0	46	50	52	54	50	
Grant	26-2	Pelican	3,680	1,489.3	61	71	64	68	63	
"	26-97	Pomme De Terre	1,794	726.0	-	-	-	-	-	Cloud Cover
Kandiyohi	34-79	Green	5,821	2,355.8	47	58	50	53	49	Portion of lake off image; clouds nearby

Classification of Lakes in the Ottertail Lakes Study Area

COUNTY	LAKE I.D. NUMBER	LAKE NAME	SURFACE AREA Acres	Hectares	(a) SECCHI	(b) CHLOROPHYLL-a	(c) TOTAL PHOSPHOROUS	TSI AVE. a,b,c	TSI AVE. a,b	REMARKS
Kandiyohi	34-142	George	248	100.4	44	54	49	50	47	Clouds nearby
"	34-154	Nest	1,019	412.4	60	66	66	69	64	Clouds nearby
"	34-169	Wagonga	1,792	725.2	-	-	-	-	-	<5', tonal anomaly
Ottertail	56-130	Big Pine			56	64	62	62	59	
"	56-138	East Battle	2,360	955.1	44	46	50	51	48	
"	56-141	Rush	5,340	2,163.0	50	56	56	58	54	
"	56-239	West Battle	5,672	2,295.5	44	53	48	50	46	
"	56-302	Silver	894	361.8	50	58	55	58	53	
"	56-306	Elbow	193	78.1	44	47	50	52	48	
"	56-658	Wall north (01) south (02)	756	306.1	54 47	64 55	60 52	63 56	57 50	
Pope	61-130	Minnewaska	7,770	3,144.5	55	66	58	63	58	
Stearns	73-196	Rice	1,568	634.6	-	-	-	-	-	Off scene
"	73-200	Koronis	3,471	1,401.7	-	-	-	-	-	Off scene
Todd	77-23	Big Birch	2,025	819.5	46	52	52	55	49	
"	77-150	Sauk north (01) south (02)	2,111	854.3	56 64	64 75	62 72	62 >69	60 >70	depths <10

Appendix C. Classification of Lakes in the Twin Cities
Metropolitan Study Area

Classification of Lakes in the Twin Cities Metropolitan Study Area

COUNTY	LAKE I.D. NUMBER	LAKE NAME	Acres	SURFACE AREA Hectares	(a) SECOHI	(b) CHLOROPHYLL-a	(c) TOTAL PHOSPHOROUS	TSI AVE. a,b,c	TSI AVE. a,b	REMARKS
Anoka	2-042	Coon	1,507	609.9	-	-	-	-	-	off scene
"	2-045	Golden	50	20.2	-	-	-	-	-	<20 pixels
"	2-075	Moore	110	44.5	-	-	-	-	-	<20 pixels
Blue Earth	7-044	Madison	1,345	544.3	-	-	-	-	-	Bad image data
"	7-047	George	141	57.1	62	70	75	70	66	
Brown	8-026	Hanska	1,844	746.3	-	-	-	-	-	<5'
Carver	10-019	Bavaria	201	81.3	54	57	59	58	56	
"	10-059	Waconia	3,196	1,293.4	54	60	59	56	57	
Dakota	19-005	Spring	5,910	2,391.0	56	62	57	55	60	Depth unknown
"	19-021	Alimagnet	113	45.7	-	-	-	-	-	Bad image data
"	19-026	Marion east (01) middle (02)	489	197.9	54 57	61 66	62 62	58 60	58 62	5' contour used
"	19-027	Crystal	290	117.4	47	50	58	51	48	
"	19-057	Fish	28	11.3	-	-	-	-	-	<20 pixels
"	19-065	Holland			-	-	-	-	-	<20 pixels
Freeborn	24-014	Albert Lea	2,654	1,074.1	-	-	-	-	-	Tonal anomaly <5'
"	24-018	Fountain	555	224.6	57	60	69	62	59	5' contour used

Classification of Lakes in the Twin Cities Metropolitan Study Area

COUNTY	LAKE I.D. NUMBER	LAKE NAME	SURFACE AREA Acres	SURFACE AREA Hectares	(a) SECCHI	(b) CHLOROPHYLL-a	(c) TOTAL PHOSPHOROUS	TSI AVE. a,b,c	TSI AVE. a,b	REMARKS
Freeborn	24-044	Freeborn	2,222	899.2	-	-	-	-	-	<5'
Goodhue	25-001	Pepin	25,060	10,141.8	54	68	77	65	62	Portion of lake off image (N end sample
Hennepin	27-004	Penn	47	19.0	-	-	-	-	-	<20 pixels
"	27-014	Powderhorn	11	4.5	-	-	-	-	-	<20 pixels
"	27-016	Harriet	337	136.4	50	52	54	51	50	
"	27-019	Nakomis	199	80.5	58	58	55	59	58	
"	27-031	Calhoun	416	168.4	48	51	51	49	50	
"	27-035	Sweeney-Twin	69	38.9	-	-	-	-	-	<20 pixels
"	27-037	Wirth	37	15.0	-	-	-	-	-	<20 pixels
"	27-038	Brownle	21	8.5	-	-	-	-	-	<20 pixels
"	27-039	Cedar	167	67.6	57	61	53	56	58	
"	27-040	Lake of the Isles	157	63.5	-	-	-	-	-	<20 pixels
"	27-042	Twin	201	81.3	-	-	-	-	-	<5'
"	27-047	Bush	207	83.8	46	49	59	52	47	10' contour used
"	27-048	Hyland	87	35.2	60	68	65	64	65	5' contour used
"	27-062	Anderson	431	174.4	-	-	-	-	-	<5'; tone anom; <20 pixels

Classification of Lakes in the Twin Cities Metropolitan Study Area

COUNTY	LAKE I.D. NUMBER	LAKE NAME	Acres	SURFACE AREA Hectares	(a) SECCHI	(b) CHLOROPHYLL-a	(c) TOTAL PHOSPHOROUS	TSI AVE. a,b,c	TSI AVE. a,b	REMARKS
Hennepin	27-067	Bryant	199	80.5	53	59	62	58	56	
"	27-071	Round	34	13.5	-	-	-	-	-	<20 pixels
"	27-089	Shady Oak	90	36.4	-	-	-	-	-	<20 pixels
"	27-118	Fish	221	89.4	49	53	62	56	51	
"	27-133	Minnetonka	14,310	5,791.3						
		(01)			51	52	52	52	51	10' contour used
		(03)			50	49	52	51	49	
		(04)			45	49	56	50	48	
		(05a)			48	50	49	48	48	
		(05b)			57	61	54	56	59	
		(05c)			53	57	52	54	55	
		(06)			65	64	46	61	64	10' contour used
		(07)			-	-	-	-	-	<20 pixels
		(08)			-	-	-	-	-	<20 pixels
		(10)			74	82	58	71	78	
		(11)			73	73	33	62	73	
		(12)			72	72	39	64	72	
		(13)			71	77	57	69	74	
		(14)			68	77	68	71	73	
		(16)			74	77	49	69	76	
"	27-137	Christmas	274	110.9	32	31	45	37	32	
McLeod	43-034	Silver	500	202.4	-	-	-	-	-	Bad image Data
"	43-084	Marion	616	249.3	-	-	-	-	-	Cloud Cover

Classification of Lakes in the Twin Cities Metropolitan Study Area

COUNTY	LAKE I.D. NUMBER	LAKE NAME	Acres	SURFACE AREA Hectares	(a) SECOHI	(b) CHLOROPHYLL-a	(c) TOTAL PHOSPHOROUS	TSI AVE. a,b,c	TSI AVE. a,b	REMARKS
Nicollet	52-034	Swan west (01) east (02)	9,346	3,782.3	64	69	56	62	68	5' contour used
Ramsey	62-01	Silver	68	27.5	59	65	56	59	62	5' contour used
"	62-06	Kohlman	84	34.0	62	69	63	64	67	4' contour used
"	62-07	Gervais	234	94.7	57	63	55	57	61	
"	62-10	Keller	72	29.1	-	-	-	-	-	<5'; <20 pixels
"	62-13	Phalen	193	78.1	53	56	53	53	54	
"	62-16	Beaver	65	26.3	60	70	76	68	66	5' contour used
"	62-34	McCarron	71	28.7	63	66	52	61	64	
"	62-55	Como	69	27.9	64	74	85	75	69	5' contour used
"	62-57	Josephine	110	44.5	53	58	60	56	56	10' contour used
"	62-67	Long	184	74.5	62	69	62	64	66	
"	62-69	Pike	34	13.8	-	-	-	-	-	<20 pixels
"	62-71	Valentine	58	23.5	-	-	-	-	-	<20 pixels
"	62-73	Snail	195	78.9	-	-	-	-	-	<20 pixels
"	62-78	Johanna	211	85.4	47	50	54	50	48	
"	62-82	Wabasso	47	19.0	-	-	-	-	-	<20 pixels

Classification of Lakes in the Twin Cities Metropolitan Study Area

COUNTY	LAKE I.O. NUMBER	LAKE NAME	SURFACE AREA Acres	Hectares	(a) SECO-II	(b) CHLOROPHYLL-a	(c) TOTAL PHOSPHOROUS	TSI AVE. a,b,c	TSI AVE. a,b	REMARKS
Ramsey	62-83	Silver	75	30.4	65	68	62	66	67	5' contour used
Scott	70-26	Lower Prior	820	331.9	65	73	60	66	70	
"	70-54	Spring	690	279.2	54	61	67	60	58	
"	70-72	Upper Prior (01) (02)	326	131.9	44 43	45 50	50 51	46 46	44 48	
Stearns	73-14	Marie	145	58.7	>77	85	68	78	81	
Washington	82-23	Lily	52	21.0	-	-	-	-	-	<20 pixels
"	82-54	Bone	206	83.4	-	-	-	-	-	off scene
"	82-101	DeMontreville	156	63.1	58	64	63	62	62	Tonal anomaly
"	82-104	Jane	159	64.4	43	47	58	49	45	Willows near same area
Wright	86-90	Buffalo west (01) east (02)	1,510	611.1	54 51	61 54	61 60	58 55	58 52	
"	86-223	Sugar	1,145	463.4	44	46	52	47	45	
"	86-252	Clearwater north (01) south (02)	3,704	1,499.0	55 48	62 54	60 58	58 53	59 50	
"	86-263	Cokato	544	220.2	52	54	66	59	52	
"	86-281	Caroline	138	55.9	-	-	-	-	-	Narrow lake
"	86-282	Lousia	183	74.1	-	-	-	-	-	"
"	86-297	Scott	101	40.9	56	63	77	67	60	

SECTION B

REMOTE SENSING EVIDENCE FOR CLEANUP OF LAKE SUPERIOR

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REMOTE SENSING EVIDENCE FOR CLEANUP OF LAKE SUPERIOR

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INTRODUCTION

The program in remote sensing at University of Minnesota, Duluth (UMD) was initiated in 1972 by the NASA LANDSAT Users Grant to the University of Minnesota. Over the past ten years, the support from NASA was used to establish a remote sensing and electronics research service center at UMD and provided seed money to generate over a million dollars in sponsored research programs. Many local and state agencies have been involved in the program. Our chief aim in the interaction with local agencies and industries was to make them aware of the usefulness of remote sensing data in environmental studies. Local agencies, such as the Arrowhead Regional Planning Commission, routinely use remote sensing data in their work and maintain staff expertise in the field.

In response to the need for interaction between the University and the local industries and agencies, the Minnesota Legislature established the Lake Superior Basin Studies Center at UMD. The Center serves as the liaison between local agencies and the University and maintains large scale programs involving the University personnel and local industry and agencies in cooperative research ventures. The remote sensing and electronics facilities are an important part of the resources for the Lake Superior Basin Studies Center.

The Remote Sensing program has had a profound effect on education at UMD. Nine Master's thesis in the Physics Department were directly related to the research initiated by the NASA Remote Sensing Users Program. Some twenty undergraduates and fifteen graduate students participated in the program. The program created at UMD a pool of six highly trained research scientists who provided expertise to the faculty and practical training to undergraduates in the use of computer techniques and electronics.

The research work performed for the Remote Sensing Program at UMD has resulted in dozens of scientific journal publications by the staff and the students.

The program also helped the staff of the UMD Physics Department to keep abreast of the recent surge in technology. As a result, a new academic program combining applied physics and engineering courses has been instituted by the Physics Department to prepare the undergraduates for current needs in the job market, both in computer modeling fields and in electronics.

REMOTE SENSING EVIDENCE FOR CLEANUP OF LAKE SUPERIOR

Broad categories of particulates suspended in the Great Lakes can be identified by their residual reflectance spectra. Sufficient information on the residual reflectance spectra can be obtained from satellite remote sensing data to develop identification algorithms which yield the concentration of particulates in the surface waters. The residual reflectances must be used if the algorithms are to be useful in a general sense rather

than for individual images (Sydor, 1980).

This paper uses satellite data to identify mining waste in Lake Superior. The data show that the lake cleaned up rapidly after the cessation of daily discharge of some 67,000 tons of mining waste into the lake. They also show that an extensive area of the lake was contaminated by waste during the discharge.

Data for 1979 and 1980 from the Nimbus 7 Coastal Zone Color Scanner (CZCS), which has narrow spectral bands centered at 443 nm, 520 nm, 670 nm, and 750 nm, were used to determine the concentration of taconite tailings in surface waters of Lake Superior. Ten images were examined. The data were first corrected for atmospheric and surface background scatter by subtracting from each band the reflected signal observed over clean portions of the lake where the concentration of particulates is less than 0.2 mg/l. The lateral dependence of background scattering due to atmosphere and water surface was established over wide transects of clean-water portions of the lake. The background dependence was then extrapolated smoothly to the sections of the lake with high concentrations of particulates. Subsequently the observed average intensities for twelve pixel areas were corrected for sun angle, look angle, atmospheric thickness and the insolation at the lake level, to produce the residual reflectance due to particulates suspended in the lake (Sydor, 1980). The residual reflectance after background corrections is given by:

$$R = \frac{I_s e^{\alpha(1/\cos\phi + 1/\cos\theta)} \cos\phi}{\cos\theta I_0 (1 - R_s)}$$

where

I_s = signal above background at satellite

R_s = specular reflectance at surface

θ = solar angle from nadir

ϕ = look angle from nadir

$e^{-\alpha}$ = attenuation factor for clear atmosphere at nadir

I_0 = insolation at the top of the atmosphere

Fig. 1 shows the residual reflectance in Band 3 for Lake Superior. Fig. 2 shows the residual reflectance spectra for several different concentrations of taconite tailings in the lake.

Identification of a specific group of particulates in Lake Superior is rather simple because the lake has large areas of clear background water and because localized concentrations of well-defined categories of organic and inorganic particulates can be isolated in a reasonably pure form (Sydor, 1978). Algorithms for indentifying mixtures of particulates can also be developed if the residual reflectances of the individual categories are spectrally separated well enough to allow elimination of ambiguities. These ambiguities arise from uncertainties in concentration measurements and from statistical fluctuations in the intensity measurements. A linear combination of reflectances and absorptions can be assumed, provided the total concentrations of particulates does not exceed 5 mg/l. Fig. 3 gives the selection criteria for identification of taconite tailings. The figure shows areas in the lake where the tailings predominated (70% or higher concentrations). The results are typical of those produced by other images in 1979. The tailings signature is quite distinct and appeared only in extreme western Lake Superior between Silver Bay, Minnesota, the site of the discharge, and the Apostle Islands, Wisconsin. Furthermore, the signature

for tailings appeared only when discharge was taking place. The discharge was discontinued in March, 1980. CZCS images after May, 1980, show no tailings in Lake Superior. The absence of the signature in the 1980 images indicates that the residual tailings concentrations in the lake were lower than 0.3 mg/l above background. The general background of particulates in extreme western Lake Superior (Fig. 4) was on the order of 0.5-0.7 mg/l. Tailings accounted for 0.2-0.5 mg/l of the background in the Silver Bay to Apostle Islands region of the lake. The other major source of the suspended solids background in extreme western Lake Superior is erosion of red clay banks along the Wisconsin shore. The presence of red clay particulates is evident on all images and correlates well with precipitation and erosion.

While tailings have not been seen after March, 1980, it is suspected that resuspension of bottom sediment could still produce detectable concentrations (0.2 mg/l) of tailings along the Minnesota shore. However, observation of such phenomenon would have to coincide with the passage of severe storms, which generally occur two to three times a year.

Nimbus 7 data for such events are not available; however, the signatures for tailings are distinct enough so that tailing particulates will certainly be detectable if resuspension occurs. It is suspected that most of the tailings detected in the surface waters in the past observations (Cook, et al, 1974) were due to the direct discharge of the tailings into the lake.

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FIGURE CAPTIONS (APPENDIX)

Figure 1. Residual reflectance in Band 3 for June 24, 1978, Nimbus 7 CZCS image. Concentration of particulates run from 15 mg/l in the extreme western Lake Superior to 0.18 mg/l over the blank sections of the lake.

Figure 2. Residual reflectance spectra for taconite tailings. The concentration of tailings is given by

$$C \text{ (mg/l)} = 12 (B_3 - B_4) \text{ where } B_3 \text{ and } B_4 \text{ are reflectances at } 550 \text{ nm and } 670 \text{ nm respectively.}$$
 Figure 3 shows the locations of sample points.

Figure 3. Distribution of tailings in surface waters of Lake Superior for June 24, 1979. The identification criteria for tailings are

$$1.04 \leq (B_2 - B_4)/(B_1 - B_4) \leq 1.3$$

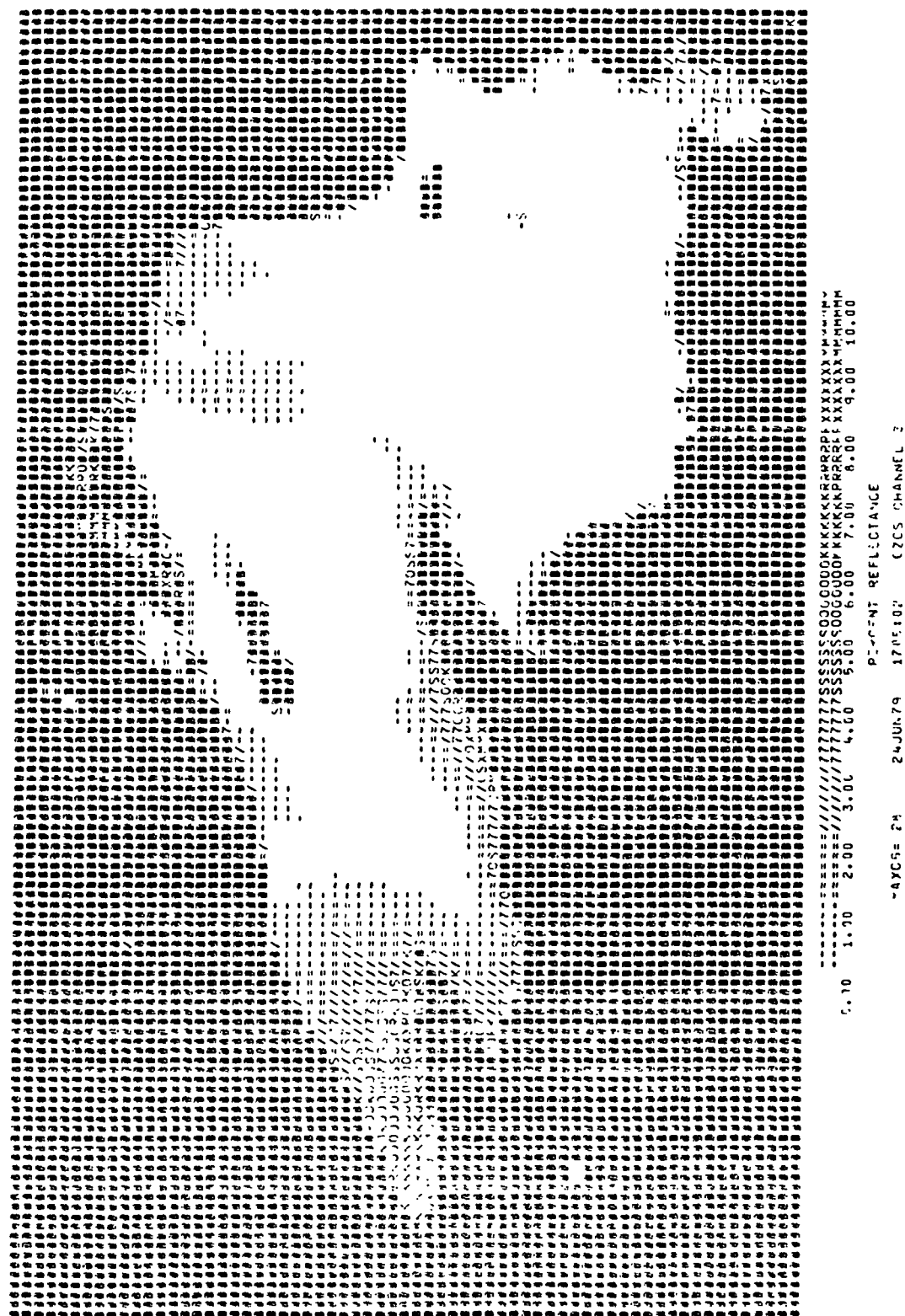
$$1.5 \leq (B_3 - B_4)/(B_2 - B_4) \leq 1.22$$

$$(B_1 - B_4) \leq .028$$

where B_1, B_2, B_3, B_4 are the residual reflectances in the first four CZCS bands. The numbered points correspond to the reflectance curves in Figure 2.

Figure 4. Concentrations of background suspended solids in Lake Superior. The background concentrations were determined from sampling measurements during lake-wide research cruises over 7 years, 1974-1980. The background concentrations were determined in conjunction with remote sensing data and apply to the most-

probable concentrations of suspended solids for those areas of the lake. (That is, times of distinct turbidity plumes were avoided.)



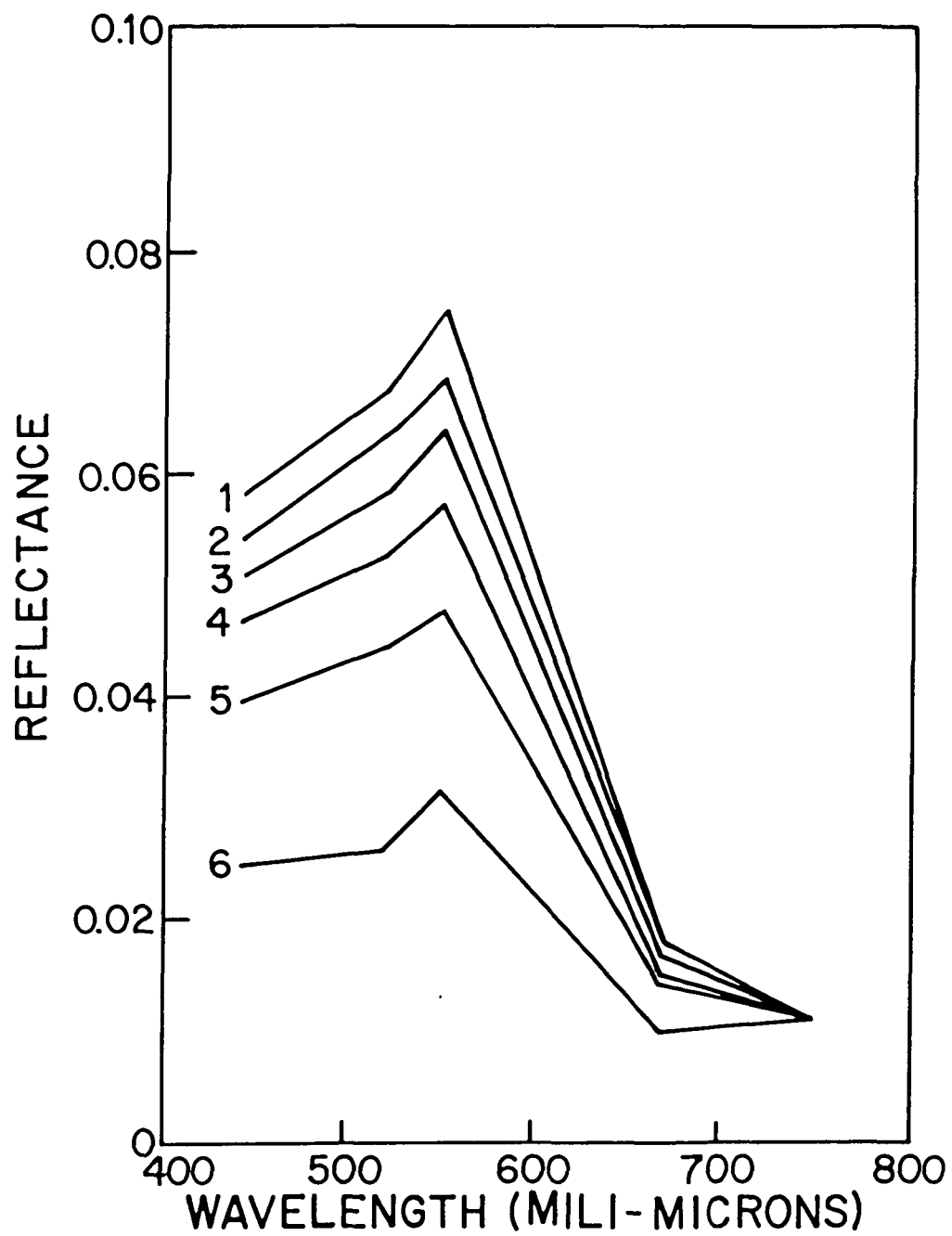


Figure 2.



Figure 3.

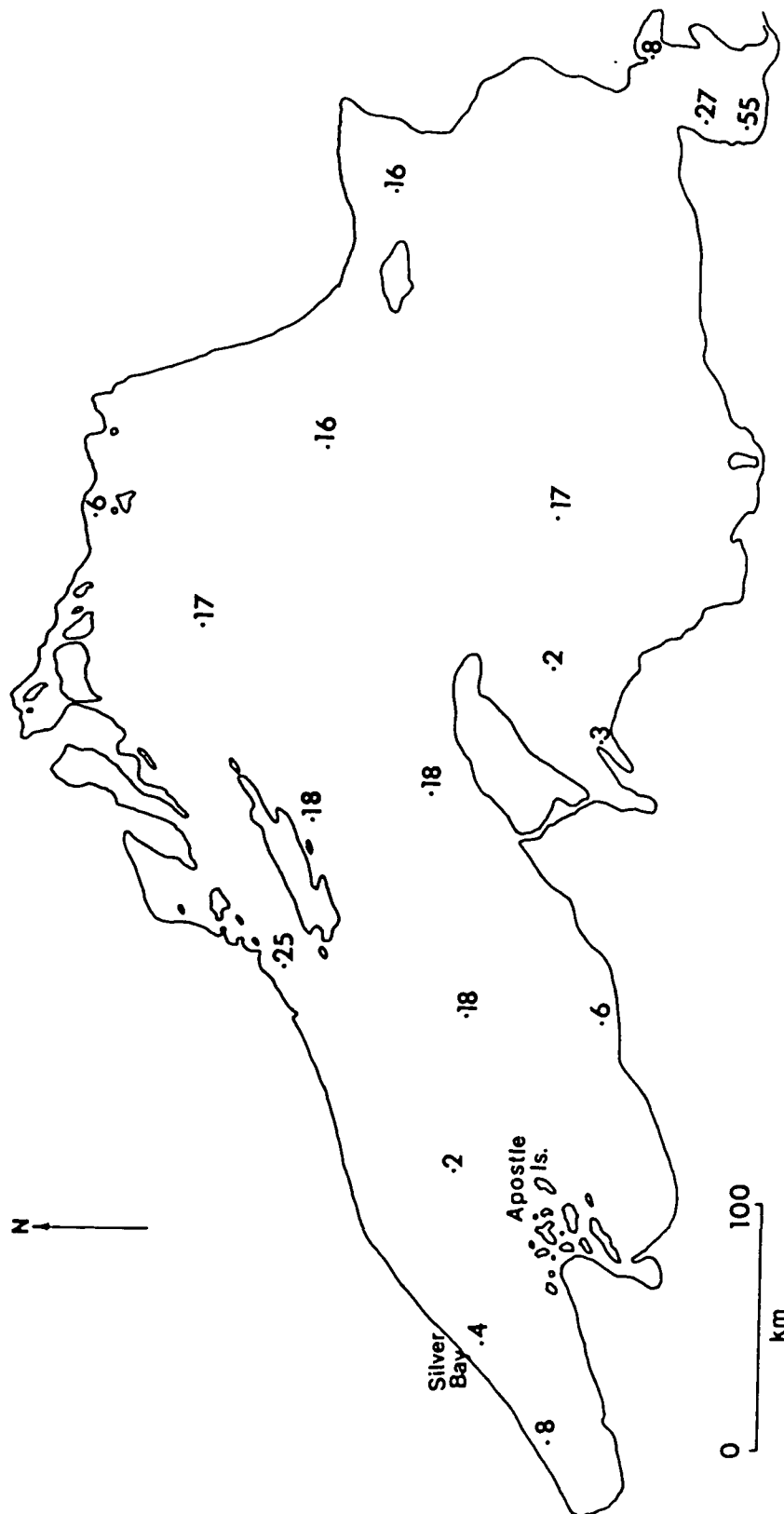


Figure 4.

SECTION C

SOIL SURVEY OPERATIONS

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SOIL SURVEY OPERATIONS

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SUMMARY OF ACTIVITIES DURING THE CONTRACT

Over the past 10 years, various applications of remote sensing to soil survey operations were conducted under support of the NASA Grant in cooperation with several agencies: the University of Minnesota Agricultural Experiment Station, the Institute of Agricultural Remote Sensing Laboratory, College of Forestry, and Department of Soil Science; and the U.S. Department of Agriculture, Soil Conservation Service.

The use of different imaging systems (camera, and LANDSAT), products (black and white, color prints and transparencies and LANDSAT computer tapes) wavelengths (visible and near infrared), interpretation methods (visual, computerized), equipment (portable light table, density slicer, image analyzer) were studied to improve soil mapping, soil interpretation, and soil and crop management.

As a result of field observations together with air photo interpretation, areas of saline-affected soils were delineated in the Red River Valley, Kittson County (Rust and Gerbig, 1973-75). The 35 mm camera system was found to be suitable for this work. Color infrared (CIR) film was better than color film. The best flight time was the period of "maximum green", in late July or early August. Photographs taken in October on essentially bare soils were of limited value.

A light, simple viewer was built to test the use of CIR transparencies for soil mapping (Meyer, Rust, Robert, 1975). After favorable field testing, and slight changes, several viewers were constructed for the soil mappers.

A field trial in which panchromatic prints, CIR transparencies, black and white infrared prints were compared for four different soils by four soil surveyors showed that CIR imagery permitted a more accurate separation of significant soil conditions and that the best flight time was early May. Through the use of CIR imagery, it was estimated that one man-year of field time could be saved in the course of a four-year survey (Robert, Skarie, Rust, Meyer, 1976).

The classification of soil moisture using remote sensing techniques, and particularly LANDSAT data, was tested in southwestern Minnesota (Rust, Robert, 1977-79). The soil moisture condition of the different sites was generally adequate during the three growing seasons. No drought situation was observed. Field records confirmed good crop conditions and high yields. Greenhouse and controlled field experiments (Becker Research Farm) have shown that corn and soybean plots with moisture stress can be best differentiated in the near infrared and thermal infrared wavebands. Analysis of the LANDSAT 1:1,000,000 scale images, bands five and seven using a density slicer, allows one to locate well and poorly drained soils when using the imagery corresponding to the period of maximum stress development.

Hail damaged areas were identified using black and white infrared, 1:1,000,000 scale, LANDSAT transparencies. Digital analysis of the LANDSAT computer tapes at the EROS Data Center using the Image 100 system and the

IDIMS system (Interactive Image Processing) could readily identify corn, soybean, and small grain fields when using temporal signatures. However, because of the signature homogeneity within crops due to favorable weather conditions, it was not possible to distinguish soil drainage classes.

In Clay County, Skarie (1978) was able to detect areas of saline soils, using CIR imagery, primarily on the basis of reduced crop cover in affected areas. Barley was a better indicator than wheat at the time of overflight. Accuracy of the recognized signatures appeared to be greater than 80%, while the area delineations themselves were somewhat less accurate.

If adequate equipment, planning, ground information, photo processing, and photo interpretation exist, 35 mm CIR aerial photography was found to be a valuable tool for soil and crop management (Rust, Robert, 1979-82). It was particularly efficient in detecting problems related to drainage, erosion, germination, weed control, crop damage, and machinery malfunction. Its most beneficial aspect seemed to be as data input to a farm information and management system containing precisely located natural and cultural practices.

Whereas some of the results are being used in current field operations in Minnesota, such as the use of CIR photographs in soil mapping, other results are indicating new techniques for more profitable, on farm, soil and crop management.

EVALUATION OF MOISTURE STRESS IN CORN AND SOYBEAN
AREAS OF WESTERN AND SOUTHWESTERN MINNESOTA

Moisture stress evaluation

During the 1977, 78, and 79 growing seasons, soil water content was monitored on all sites as part of the ground data collection (Rust, Robert, 1977, 78, 79). At that time, the soil water content was expressed in water per unit mass of soil because the results of laboratory analysis (soil bulk densities, 1/3 and 15 bar water retentions) were not yet available. A preferred expression is water per unit of volume of soil. This is a better evaluation of the soil water content, since it takes account soil texture and structure. Using the volume water concept the soil water status is expressed as the percentage of actual available soil water to maximum available soil water. The actual available water content is the total volumetric water content, evaluated to a depth of 60 inches, minus the non-available water (15 bar soil water content). The maximum available water for a given soil is the difference between the soil water content at 1/3 bar retention (field capacity) and 15 bar soil water content (wilting point). Thus the percentage of actual available to maximum available soil water content is an indication of soil recharge. However, prior to its computation, soil bulk density and 1/3 and 15 bar soil content were measured in the laboratory on representative samples of each soil under consideration. Programs were written to compute the results and print, for each date, the site, soil, depth, and the percentage of actual available to maximum available soil water content (Minnesota Accelerated Soil Survey, Department

of Soil Science). Then 3-dimensional graphs were plotted to display the yearly variations for visual analysis. As an example, Figure 1 shows the variation of percentage of actual available to maximum available soil water content for the 1979 growing season in ves soil, site 2a. The growing season analyses related to soil water movement, soil climatology, and soil management, and will be kept in a state-wide soil data base under development.

Color infrared for near-real time soil and crop management

The feasibility study of using CIR aerial photography as a near-real-time tool for soil and crop management in rainfed corn and soybean areas of southwestern Minnesota was described in the previous report (Rust and Robert, 1980). Since this study generated strong interest from farmers and agri-business firms, a guide will be published describing the benefits, limitations, equipment, and procedure for this technique.

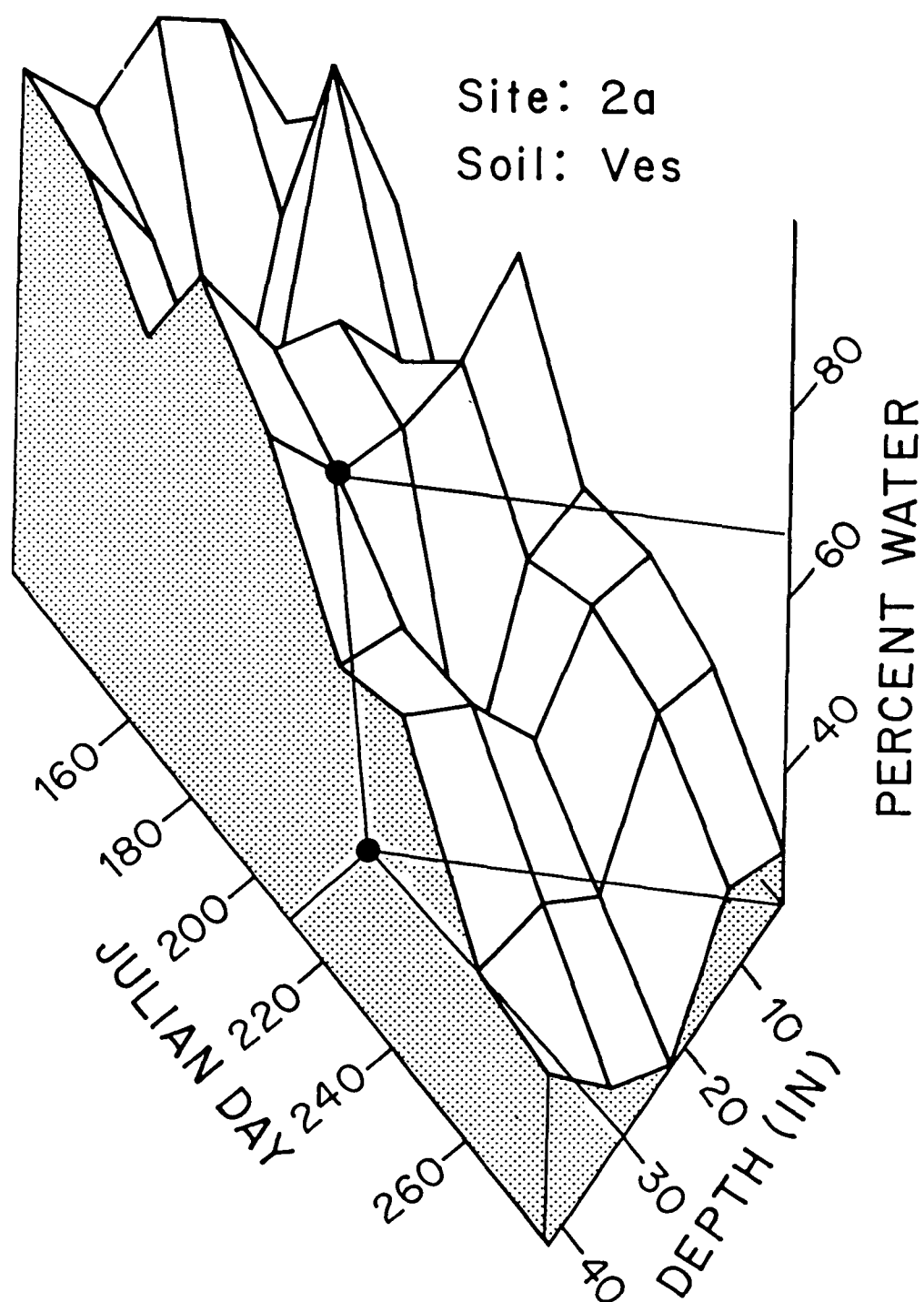


Figure 1. Percentage of actual available to maximum available soil water content for the 1979 growing season (65% on July 30 at a 30" depth).

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SECTION D

SUMMARY OF LANDSAT WORK BY
THE MINNESOTA GEOLOGICAL SURVEY

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SUMMARY OF LANDSAT WORK BY
THE MINNESOTA GEOLOGICAL SURVEY

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The work of the Minnesota Geological Survey has continued to benefit from the ERTS-LANDSAT projects funded by NASA. Our initial work on the lineaments seen in LANDSAT imagery in northeastern Minnesota led to new interpretations of the structure of the Duluth Gabbro Complex, with important implications for the occurrence of copper, nickel and vanadium deposits and extensive revision of our ideas about the origin, genetic processes and tectonics of the complex. The complex is one of the major geologic bodies in the United States, and its geology has many implications worldwide. This work led to a Ph.D. thesis by R.W. Cooper (1978) and a major revision of Duluth Complex geology published in the American Journal of Science in 1980 by Weiblen and Morey.

The Minnesota Geological Survey was interested in a variety of geological and hydrological applications pertaining to synergistic relationships among remote-sensing and geophysical media. One of the Survey's studies involved the feasibility of using various kinds of imagery, photographs, and soil and topographic maps to determine the depth to near-surface ground water. If successful, this study would have great benefits in fields of water management, engineering, and agriculture. The results, however, showed that remote images were useful for identifying only those areas with

shallow water tables. This study is discussed in more detail in the Survey's Final Report, dated January 1, 1981.

Synergistic applications that showed considerable promise involved the use of high-altitude aerial photographs and LANDSAT images to identify lineaments in northern Minnesota. It was found that lineaments, or alignments of topographic features, are related to glacial or postglacial processes. There is also a striking correspondence between lineaments and bedrock structures where the structures are known in ice-scoured areas that may have only a thin veneer of ground moraine. This information, coupled with recently acquired high-resolution aeromagnetic data, should provide a starting point for the reappraisal of many of the structural details associated with the bedrock. A variety of structural and bedrock details have relevance to mineralized areas, some of which could prove to be economic. Three lineament maps at 1:250,000 scale of areas in northern Minnesota were printed as a result of support on this grant and are included in this report.

Tonal lineaments associated with peatlands reflect vegetational patterns associated with Holocene peat bogs. This provides a means of delineating the vast peat resources that occur in some parts of northern Minnesota.

Overall, the Minnesota Geological Survey had mixed success in the use and applications of LANDSAT images. Subtleties of changes in vegetation, soil, and topography are such that ground-water presence and depth to water table are nearly always impossible to quantify except for broad-scale applications. On the other hand, bedrock and structural differences as shown in

lineaments offer great potential for resolution of some kinds of geologic studies. Some major structural trends, in fact, were previously unknown because of their scale, until the advent of LANDSAT images and other sources of information. There is already a large body of literature dealing with the use of remote-sensing aids in mineral and hydrocarbon exploration in various parts of the world. Minnesota may not present the same economic potential as some of these areas, but the techniques and a variety of spin-off results from the Survey's work on synergistic applications have been very useful as an educational tool for future studies of a similar nature. We are now organizing a project to use multivariate, spatially-based grid-modeling techniques developed at the EROS Data Center, to apply the synergistic concept to the search for new mineral resources in northeastern Minnesota. A variety of products derived from LANDSAT will be integral components of this effort.